

High - temperature phase transition in a plasma and the mechanism of powerful solar flares

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Abstract

It is shown that the high- temperature phase transition in a plasma gives the mechanism of transition from the highly conductive state to the highly resistive state of a plasma in the ‘electric circuit’ model of solar flares which was first introduced by H.Alfven and P.Carlqvist in 1967. With this addendum, the modern version of the electric circuit model can explain both the fast dissipation of energy and the acceleration of particles in a solar flare.

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Among various models of solar flares, the ‘electric circuit’ model [1,2], which was first introduced by Alfven and Carlqvist in 1967, seems to be the most adequate for explaining of the fast dissipation of energy and the acceleration of particles. The main problem of the electric circuit model was so far the mechanism of transition from the highly conductive state to the highly resistive state of a plasma in a magnetic loop [1,2]. It was shown recently [3] that a hot plasma can undergo the phase transition from the cold phase to the hot phase. The transport properties of the hot phase essentially differ from those of the cold phase due to the intense interaction of the plasma with thermal radiation above the inversion temperature [4]. The specific resistivity of the hot phase, η_h , is about three orders of magnitude larger than that of the cold phase, η_c , so the high- temperature phase transition in a plasma can supply a mechanism triggering the fast increase in the electric resistivity of a plasma column in a magnetic loop. Below we consider this mechanism in more detail.

The critical value $T_{e,c}$ of the electron temperature, corresponding to the transition from the cold to the hot phase, for relatively low plasma densities achievable in tokamaks is independent of the density and has an order of magnitude of the inversion temperature $T_0 \cong 2keV$ [4]. Studies of sawtooth oscillations in tokamak discharges by von Goeler, Stodiek, and Southoff [5] suggest that the transition temperature is approximately $T_{e,c} \cong 0.8keV$. The line of phase equilibrium between the hot and cold phases of a plasma is described by the following approximate expressions:

$$T_c \cong T_{c,0}, \quad n < n_{c,0}, \quad (1)$$

$$n_c \cong 12T / (hc\sigma_a), \quad n > n_{c,0}, \quad (2)$$

where $n_{c,0} \cong 0.8 \times 10^{17}cm^{-3}$ for $T_{c,0} \cong 0.8keV$, c is the speed of light, h is the Planck constant, T is the temperature, the Boltzmann constant being assumed to be included in the definition of the temperature, n is the plasma density, and σ_a is the absorption cross-section.

The specific resistivity of a hot plasma has a form [6]

$$\eta = m_e \nu_{ei} / (ne^2), \quad (3)$$

where the frequency of electron-ion collisions in the cold phase of a plasma is given by the

formula [6,7]

$$\nu_{ei} = nv_{Te}\sigma_{ei} \approx 2\pi e^4 n \log(n\lambda_D^3) / (m_e^2 v_{Te}^3), \quad (4)$$

where $n = n_e = n_i$ is the electron and ion density, v_{Te} is the thermal velocity of electrons, σ_{ei} is the electron-ion collisional cross-section, m_e and e are the mass and charge of electron respectively, and λ_D is the Debye length. It is clear from equation (4) that the Coulomb collisional cross-section is very small at high temperatures, $\sigma_{ei} \propto T_e^{-2}$, where T_e is the electron temperature.

It has been shown recently [8] that the frequency of electron-ion collisions in the hot phase of a plasma interacting with thermal radiation is given by the formula

$$\nu_{ei} = nv_{Te}\sigma_{ei} \approx nv_{Te}\sigma_0, \quad (5)$$

where $n = n_e = n_i$ is the plasma density, v_{Te} is the thermal velocity of electrons, and σ_{ei} is the cross-section of electron-ion collisions which is a constant, σ_0 , determined by the atomic size. The origin of the constant cross-section σ_0 is as follows. A hot plasma with the temperature $T_e \geq T_0 \cong 2\text{keV}$ is intensely interacting with the field of thermal radiation. At temperatures $T \geq T_0$ the stimulated radiation processes dominate this interaction [9]. Thermal radiation induces radiative transitions in the system of electron and ion which corresponds to the transition of electron from the free to the bound state.

Thus, in a hot plasma interacting with thermal radiation, the bound states of electrons and ions restore, leading to the change of collisional properties of a hot plasma. In this case, the electron-ion collisional cross-section has an order of magnitude of the atomic cross-section, $\sigma_0 \cong 10^{-15} \text{cm}^2$.

Since the specific resistivity η of a plasma is proportional to the frequency of electron-ion collisions, as given by equation (3), the resistivity of a plasma in the hot phase increases with the electron temperature as

$$\eta_H \propto T_e^{1/2}, \quad (6)$$

contrary to the relation for the cold phase of a plasma

$$\eta_C \propto T_e^{-3/2}. \quad (7)$$

From equations (3), (4), and (5) we find the ratio of the specific resistivities for the hot and cold phases of a plasma respectively at the transition temperature to be approximately $\eta_H/\eta_C \cong 2 \times 10^3$.

According to equations (3) and (4), the specific resistivity of the cold phase nearby the transition temperature is $\eta_C \cong 10^{-5}\Omega m$. If the length of a corona loop is about $l \cong 10^{10}cm$, and its cross- section is $S \cong 10^{18}cm^2$ [2], then the resistivity of the magnetic loop is $R \cong 10^{-11}\Omega$. The mean electric current through a magnetic loop is about $I \cong 3 \times 10^{11}A$, so the mean rate of energy dissipation in the cold phase in the vicinity of the transition temperature is

$$dW/dt = I^2 R \cong 10^{19}ergs^{-1}. \quad (8)$$

This value is some nine orders of magnitudes less than the energy dissipation rate in powerful solar flares [2].

There are two mechanisms of the enlarging resistivity of a magnetic loop. One is the phase transition to the hot phase of a plasma which gives an increase of resistivity $R_H/R_C \cong 2 \times 10^3$, as indicated above. The temperatures of the plasma in solar flares inferred from the observational data are about $5keV$ [2], what exceeds the critical temperature of the high-temperature phase transition in a plasma. Another mechanism is the radial contraction of the current channel in a magnetic loop due to poloidal (transverse) magnetic field generated by the current. If the diameter of the current channel changes from the initial value of $d_0 \cong 10^9cm$ to the final value of $d \cong 10^7cm$, then the increase of the resistivity of the magnetic loop is $R/R_0 = S/S_0 = d^2/d_0^2 \cong 10^4$. These two mechanisms of the growth of the magnetic loop resistivity are sufficient since the rate of energy dissipation in powerful solar flares was overestimated in the models based on the synchrotron emission generated by fast electrons (see below).

In fact, the contraction of the current channel leads to its disintegration into the separate filaments, so that the total cross- section of the magnetic loop remains nearly constant, while the sum of cross- sections for the current filaments decreases essentially with respect to the initial cross- section of the current channel. Thus, the sequence of events during a powerful solar flare is as follows: (i) the contraction of the current channel in a coronal magnetic loop; (ii) the disintegration of the current channel into the separate filaments; (iii) the high-temperature phase transition in the plasma of the current filaments.

The value of the poloidal magnetic field generated by the current in a magnetic loop is given by the formula

$$B_p = 2I / (cr), \quad (9)$$

where r is the radius of the current channel. The value of the poloidal magnetic field is $B_{p0} \cong 60G$ for $r_0 \cong 10^9 cm$, and $B_p \cong 6 \times 10^3 G$ for $r \cong 10^7 cm$. The mean toroidal (longitudinal) magnetic field in the loop is about $B_T \cong 400G$ [2]. The safety factor defined by the formula

$$q = B_T r / (B_p R), \quad (10)$$

where R is the radius of the magnetic loop, is small, so the Kruskal- Shafranov condition for kink instability is satisfied [10]. It means that the current does not flow along the magnetic loop axis, but instead a current line is helical.

The mechanism of the electric field generation in a magnetic loop is described in Ref.2. The accelerating electric field can be roughly estimated as

$$E \cong vB/c, \quad (11)$$

where v is the velocity of convection motions, $v = 0.1 - 0.5 km s^{-1}$ [2]. If the value of the magnetic field is $B \cong 10^3 G$, then the accelerating electric field is $E \cong 0.3 V cm^{-1}$. For the characteristic scale of the magnetic loop, $l \cong 10^9 cm$, the maximum energy of accelerated particles is $W_{im} = eEl \cong 300 MeV$, what is comparable with the maximum energy of fast ions in a powerful solar flare [2]. The maximum energy of accelerated electrons is restricted by their mean free path with respect to the electron- ion collisions,

$$l_e = v_{Te} / \nu_{ei} = 1 / (n\sigma_0) \quad (12)$$

in the hot phase of the plasma. For the plasma density $n \cong 10^{10} cm^{-3}$, the mean free path of electrons is $l_e \cong 10^5 cm$, and the maximum energy of electrons is $W_{em} \cong eEl_e \cong 30 keV$. This value is consistent with the available data on the electron energy distribution in powerful solar flares [2].

The disruptive instability [11] of the current channel in the hot phase of the plasma can be responsible for the ejection of the plasma with accelerated particles in the external space

(see also Ref.8).

Due to the Colgate paradox [2], the X- ray emission from solar flares cannot have a synchrotron origin. Presumably, it is produced by the reverse Compton scattering modified by the stimulated radiation processes in the hot phase of the plasma interacting with thermal radiation.

To summarize, we show that the account for the high- temperature phase transition in a plasma can essentially improve the possibility of the 'electric circuit' model to explain the phenomena observed in powerful solar flares.

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